PROGRESS ON A LASER-DRIVEN DIELECTRIC STRUCTURE FOR USE AS A SHORT-PERIOD UNDULATOR

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Abstract

A laser-powered dielectric structure, based on the Micro Accelerator Platform, has been design and offers undulator periods in the micron to millimeter range. This design was shown previously to potentially support a deflection field strength of several GV/m, equivalent to a magnetic undulator with field strength of about 40 T. In this paper, we address a previous problem in the design involving the junction between half periods of the undulator. Because the structure is resonant, flipping from one deflection direction to the opposite one required controlling the phase of the incident laser and reestablishing a new resonance. One solution to this "phase flipping" problem involves the use of two lasers at different wavelengths to excite adjacent half-periods. This new approach is explored further here along with simulations of the beam trajectory and resulting undulator radiation. We also consider parameter sets that may be possible for these extremely short period undulators.

INTRODUCTION

X-ray sources based on laser undulators have gained increasing interest primarily because their short period makes easier the production of short-wavelength radiation. Thus, these x-ray sources are compact in size, only require low-energy electron beams, and may have low operating costs. Several laser-based undulators have recently been proposed or constructed [1, 2, 3]. These proposed undulators utilize Compton scattering between a free-space laser and a relativistic counter-propagating electron beam. The undulator period is required to be half the laser wavelength; thus, laser power limits the undulator parameter.

To overcome this small undulator parameter, a Bragg structure-based laser undulator has been previously proposed as illustrated in Fig. 1 [4]. The structure is similar to the slab-symmetric acceleration structure that has been investigated at UCLA since 1995 [5, 6, 7, 8]. The top face of the planar structure contains a periodic array of couplers which are incident by a high-powered laser to excite an electromagnetic standing wave in the structure. The undulator provides phase synchronicity between the laser-driven cavity fields and the electron beam as demonstrated in Fig. 2. As an electron travels through the structure, the electron is deflected in one direction by many optical periods within one half undulator-period. In the next half period, the electrons are deflected in the opposite direction. Thus, the undulator parameter is not restricted by the laser wavelength. Also, the structure has previously been shown theoretically capable of producing electron-beam deflection corresponding to an equivalent magnetic field strength of 40T leading to an increased undulator parameter [4].

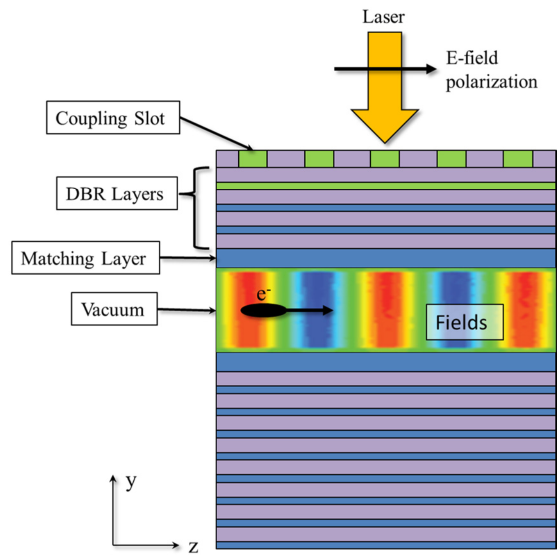

Figure 1: Schematic diagram of the Bragg structure. Five optical periods of the structure are shown; blue represents HfO_2, purple represents SiO_2, and green represents TiO_2.

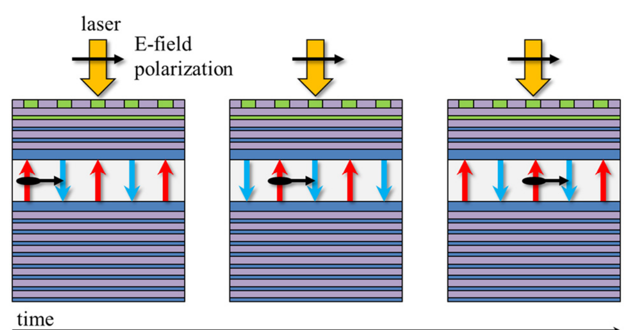

Figure 2: Schematic demonstrating the phase synchronicity between the electron beam and the laser-driven cavity fields. This synchronicity occurs because the electron beam is assumed to travel at velocity $v \approx c$ and the fields evolve at the same rate. Red and blue arrows represent the fields and their directions.

In this study, the problem in the design involving the junction between half periods of the undulator is explored. With this resonant structure, flipping from one deflection direction to the opposite direction requires controlling the phase of the incident laser and re-establishing a new resonance. One approach is the use of two lasers at different wavelengths to excite adjacent half-periods. Additionally, since the fields are not sinusoidal,

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simulations of the beam trajectory and resulting undulator radiation are explored for a possible parameter set for these short period undulators.

THE BRAGG STRUCTURE UNDULATOR

The Bragg structure contains two parallel planar Distributed Bragg Reflectors (DBRs) separated by a vacuum gap as illustrated in Fig 1. The planar Bragg resonance cavity is a one-dimensional photonic band-gap structure. Slots, filled with a high index material (TiO_2), at the top of the structure produce a diffraction pattern which propagates through the structure. The pair of DBRs reinforce and resonate these diffracted fields in the vacuum gap. Matching layers, made of another high index material (HfO_2), just outside the vacuum gap, allow for tuning of the resonant frequency. The materials used in the DBR are of alternating low- and high-index (SiO_2 and HfO_2). The laser used to excite the structure is an 800nm Ti:Sapphire laser polarized parallel to the beam axis. The UCLA research group has recently fabricated such a structure [8], using several nanolithography and thin film deposition techniques.

Along the direction of the vacuum gap, the Bragg structure can be treated as a waveguide. Misrahi and Schächter have shown via theoretical analysis that the planar Bragg waveguide can support a TEM mode in the vacuum gap [9]. The power profile is flat, with $E_z \equiv 0$ and $H_z \equiv 0$. A standing TEM electromagnetic wave can be created in the vacuum gap of the structure when the structure is incident by the laser. The field in the vacuum gap can be separated into oppositely directed traveling waves. One is synchronous with the electron bunch, and the other is counter-propagating as seen in Fig. 2. The form of the standing wave is

$$E_y = \frac{E_m}{2}\left[\exp(-jk_z z) - \exp(jk_z z)\right]\exp\left(j(\omega t - \varphi)\right) \quad (1)$$

$$H_x = \frac{E_m}{2\eta}\mu\left[\exp(-jk_z z) + \exp(jk_z z)\right]\exp\left(j(\omega t - \varphi)\right) \quad (2)$$

where $k_z = \omega/c$, $\eta = \sqrt{\mu_0/\varepsilon_0}$, and φ is the phase corresponding to the bunch position within the wave. Since the wave evolves with time at the speed of light, if the relativistic electron bunch is assumed to travel long the z direction with velocity $v \approx c$, the electron bunch will be synchronous with the forward electromagnetic wave. Thus, if the bunch length is small compared to the laser wavelength, the electron bunch will experience a uniform deflection force.

If the bunch is located at $\varphi = \pi/2$, the maximum of the forward electromagnetic wave, then the total deflection force is

$$F_y(t) = F_E + F_B = qE_m \quad (3)$$

Therefore, the deflection force is constant. In order for the structure to behave as an undulator, the phase must flip every half undulator period as demonstrated in Fig. 3. The undulator period is given by $\lambda_u = 2n\lambda_L$ where n is the number of optical periods per deflection (half undulator period) and λ_L is the optical period length (or laser wavelength).

The effective magnetic flux density for a laser undulator is

$$B_{eff} = \frac{F_{deflection}}{ev} \approx \frac{E_x}{c} \quad (8)$$

assuming a relativistic electron bunch with $v \approx c$.

The undulator parameter is

$$K = \frac{|F_y|\lambda_u}{2\pi mc^2}. \quad (9)$$

Unlike past laser undulators that depend on Compton scattering, the magnitude of the undulator parameter is not an issue with this planar Bragg structure. Since the undulator period is not restricted by the laser wavelength, the undulator parameter can be increased dramatically by increasing the number of optical periods $2n$ per undulator period. The main circumstance restricting λ_u is that it needs to be small enough to prevent the electron beam from striking the cavity wall.

Simulations showing the effectiveness of the structure were shown in a previous paper [4].

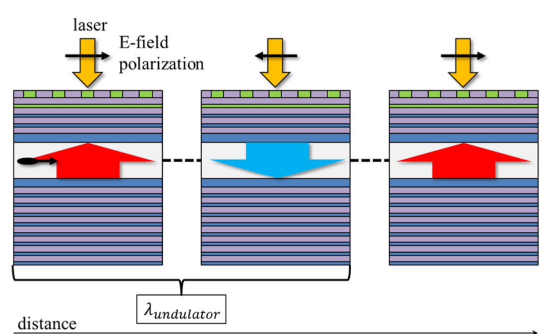

Figure 3: Schematic of the phase flipping in a laser undulator based on a planar Bragg cavity. Red and blue arrows represent the fields acting on the electron beam over a distance.

SPECTRAL SIMULATION RESULTS

Junction Between Half Periods

Within a multi-period structure, the phase of the incoming laser must be controlled to reestablish a new resonance and flip the direction of the deflection force. This issue can be solved by having a structure with alternating resonant frequencies every half period of the undulator. Using *ANSYS® HFSS™* [10], a stable resonant structure has previously been designed (at 362.05 THz)

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[4]. Half of the undulator period should be resonant at this frequency, and the other half at another frequency.

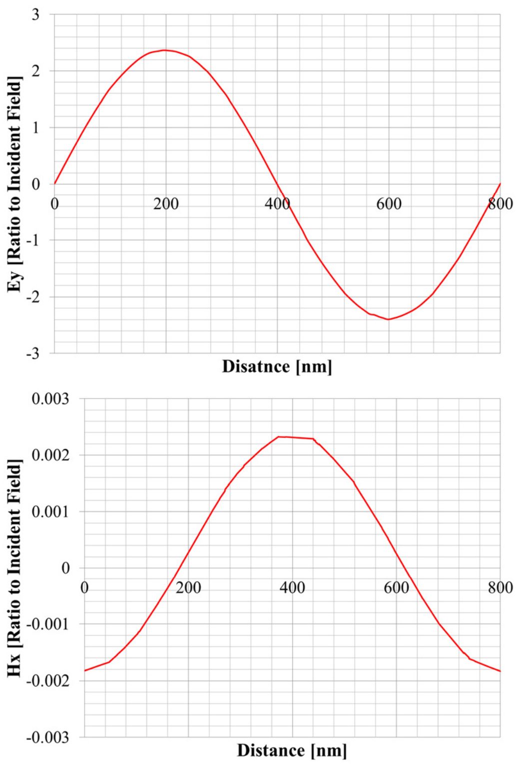

Figure 4: Plot of E_y and H_x in a single period structure.

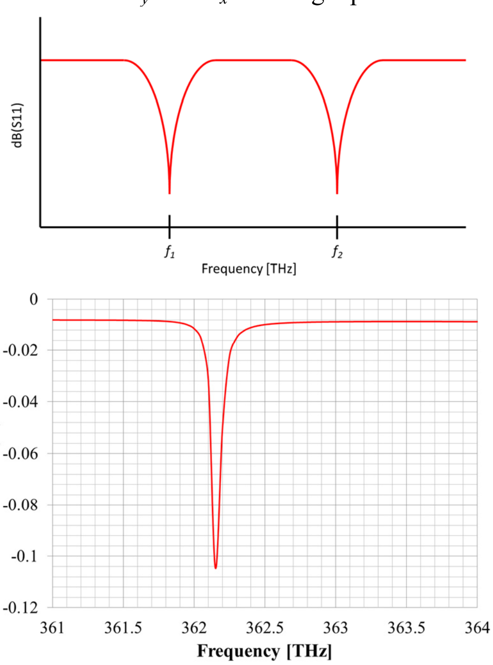

Figure 5: Ideal S11 plot of a dual-frequency resonant structure (top). S11 plot for a single period structure (bottom). The resonance is shallow and the structure still requires more optimization.

The electric field and magnetic field along the vacuum gap of a single period structure is shown in Fig. 4. In order to optimize the single period structure for another frequency, parameter sweeps must be performed on the coupling and matching layers of the original resonant structure. The power reflected back to the top (port 1) for a combined and idealized structure with both resonances is shown in the S11 plots in Fig. 5. The frequency separation between the two resonances must be selected to be much wider than each resonance width. The resonant width is demonstrated in Fig. 5 in an S11 plot from a single period structure; however, the resonance is shallow and still requires optimization. An idealized result is shown as the modified structure is the subject of ongoing work. A unified structure with two resonances should produce smooth field transitions at the half-periods, however, care must be taken to create a structure with similar physical dimensions throughout.

Spectrum and Trajectory

Since the fields acting on a traveling electron within the vacuum gap are not sinusoidal, but square in nature, the trajectory and resulting spectrum are of interest. Simulations were performed using Tanaka and Kitamura's SPECTRA software application [11]. The SPECTRA parameters and their input/output values are shown in Table 1.

Table 1: Parameters and their SPECTRA Input/Output Values of a Bragg Structure Based Undulator

Parameter	**SPECTRA Value**
Radiation wavelength	0.1 Å
Normalized emittance	0.01 mm mrad
Energy spread	10^{-4}
Electron energy	602 MeV
Electron beam spot size	291.3 nm
Undulator period λ_u	250 μm
Undulator parameter K	0.467

SPECTRA can generate its own sinusoidal undulator fields or allow for user-defined fields; however, only magnetic fields can be modeled. The electric fields were converted using equation (8), forming a total magnetic field with a square waveform. With the parameters from Table 1, a SPECTRA sinusoidal field was generated in addition to the user-defined near square wave (a slight slope is necessary at the transition between half periods in order for SPECTRA to perform the calculations). The trajectory of a single electron is shown in Fig. 6 for both fields. The peak trajectory of the sine (square) field is 16µm (20µm). The resulting spectra of both fields are shown in Fig. 7. The FWHM of the sine (square) field is 19.8 eV (18.6 eV). The central peaks of the spectra are separate by about 700 eV, which is only around 7 pm in wavelength. The discrepancy is believed to be due to the difference in electron trajectory.

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Despite the field harmonics contained in the square-wave of the optical undulator's alternating deflections, the trajectory and resulting spectrum are in close agreement to a perfect undulator.

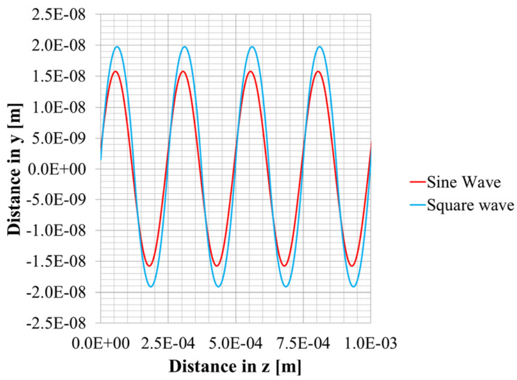

Figure 6: A few periods of the trajectory of a single electron in the undulator, for both the SPECTRA generated field (red) and the ideal optical undulator field (blue).

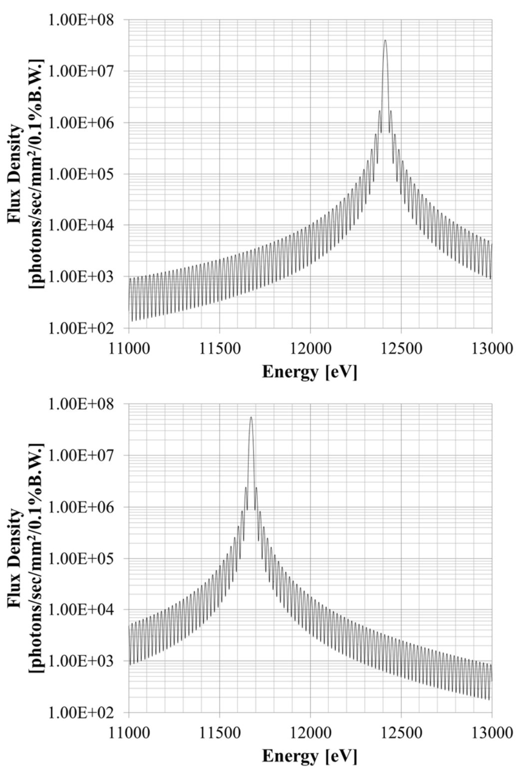

Figure 7: Plots of the undulator spectral output (on a log scale), for both the SPECTRA generated field (top), and an ideal optical-scale undulator field (bottom), for the parameter set in Table 1. Results produced using the SPECTRA simulation tool.

Conclusion

A Bragg structure undulator has been described and the issue of flipping the deflection force at junctions of half undulator periods has been addressed. Further investigation of this problem is required. The spectrum and electron trajectory of the proposed undulator has also been explored, and are promising. Future work will involve fabrication and testing of a physical structure.

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